The GOddard SnoW Impurity Module (GOSWIM) for the NASA GEOS-5 Earth System Model: Preliminary Comparisons with Observations in Sapporo, Japan

Teppei J. Yasunari[1,2], K.-M. Lau[2], Sarith P. P. Mahanama[3,2], Peter R. Colarco[2], Arlindo M. da Silva[2], Teruo Aoki[4], Kazuma Aoki[5], Naoto Murao[6], Sadamu Yamagata[6], and Yuji Kodama[7]

[1]*Goddard Earth Sciences and Technology and Research, Universities Space Research Association, Columbia, MD, USA*
[2]*NASA Goddard Space Flight Center, Greenbelt, MD, USA*
[3]*Science Systems and Applications, Inc., Lanham, MD, USA*
[4]*Meteorological Research Institute, Tsukuba, Japan*
[5]*Faculty of Science, University of Toyama, Toyama, Japan*
[6]*Faculty of Engineering, Hokkaido University, Sapporo, Japan*
[7]*National Institute of Polar Research, Tokyo, Japan*

Abstract

The snow darkening module evaluating dust, black carbon (BC), and organic carbon (OC) depositions on the mass of snow impurities and albedo has been developed for the NASA Goddard Earth Observing System, Version 5 (GEOS-5) Earth System Model, as the GOddard SnoW Impurity Module (GOSWIM). GOSWIM consists of the updated snow albedo scheme from a previous study (Yasunari et al. 2011) and a newly developed mass concentration calculation scheme, directly using aerosol depositions from the chemical transport model (GOCART) in GEOS-5. Compared to observations at Sapporo, the off-line simulations, forced by observation-based meteorology and aerosol depositions from GOES-5, reasonably simulated the seasonal migration of snow depth, albedos, and impurities of dust, BC, and OC in the snow surface. However, the simulated dust and BC mass concentrations in snow were especially underestimated except for the BC in the early winter, compared to the observations. Increasing the deposition rates of dust and BC could explain the observations. Removing BC deposition could possibly lead to an extension of snow cover duration in Sapporo of four days. Comparing the off-line GOSWIM and the GEOS-5 global simulations, we found that determining better local precipitation and deposition rates of the aerosols are key factors in generating better GOSWIM snow darkening simulation in NASA GEOS-5.

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1. Introduction

In the Cryosphere, strong radiative forcing is exerted on the snow surface through the snow darkening effect (SDE) by the deposition of light absorbing aerosols (LAA) such as dust and black carbon (BC), which reduce snow albedo and heat the snow surface, leading to accelerated snow melt (e.g., Warren and Wiscombe 1980; Painter et al. 2007; Flanner et al. 2007, 2009). The forth report of Intergovernmental Panel on Climate Change (IPCC 2007) based on Hansen and Nazarenko (2004) and Hansen et al. (2005) has emphasized the importance of radiative forcing by BC on snow. Recently, Bond et al. (2013) and Boucher et al. (2013) further summarized the BC forcing on snow. However, these estimates still have larger uncertainties.

Currently only a limited number of land surface models (LSM) for global models consider both dust and BC SDE (e.g., Flanner et al. 2009; Aoki and Tanaka 2008, 2011; Watanabe et al. 2010; Bentsen et al. 2013; Ménégoz et al. 2013). The need to include effects of organic carbon (OC) (matter) for SDE in future modeling was also suggested by Flanner et al. (2009) and Aoki et al. (2011). As indicated by the previous studies, estimates of SDE in climate models cannot be ignored in terms of climate feedbacks. Before discussing global climate impacts, SDE should be validated locally. Unfortunately, in general, local observations needed to validate LSM-estimated SDE for co-located observations of LAA in the atmosphere and snowpack are extremely scarce. Although Skeie et al. (2011) and Forsström et al. (2013) in detail validated modelled BC in snowpack with observations they were not for the total SDE (dust+BC+OC in snow). Some studies investigated modelled one-dimensional SDE with prescribed snow impurity data based on the observations (e.g., Yasunari et al. 2011; Niwano et al. 2012). However, these model studies did not calculate the mass of snow impurities with aerosol deposition data.

The NASA Goddard Earth Observing System, version 5 (GEOS-5) (Rienecker et al. 2008) is an Earth System Model (ESM), which has been developed under the ESM Framework (ESMF) (Hill et al. 2004). However, the original LSM in GEOS-5 (Ducharne et al. 2000; Koster et al. 2000) did not include SDE. In a previous study, the preliminary version of the snow albedo scheme for SDE was developed and incorporated into the LSM (Yasunari et al. 2011). However, as mentioned above, there was no way to calculate the mass concentrations in snow with aerosol deposition data in their study. In climate model simulations, snow impurities need to be computed internally, using modelled aerosol depositions with snow mixing processes. Therefore, in this paper: (1) we introduce a new mass concentration calculation scheme for the snow impurities using aerosol deposition data; and (2) we update the snow albedo scheme by Yasunari et al. (2011) (OC consideration, dust size bins extended to five bins, and updated absorption values, etc.). Here we name the snow darkening module for NASA GEOS-5 as GOddard SnoW Impurity Module (GOSWIM).

The purpose of this paper is to introduce the GOSWIM for NASA GEOS-5, and validate and discuss the "local snow melting by SDE". We have discussions on off-line LSM simulations including sensitivities and outputs from a global GEOS-5 simulation at a single location using the developed GOSWIM, including the total dust+BC+OC SDE. For validations, we use the unique observed data available in Sapporo, Japan, which include various

Corresponding author: Teppei J. Yasunari (GESTAR/USRA), Code 613, NASA Goddard Space Flight Center, 8800 Greenbelt Rd., Greenbelt, MD 20771, USA. E-mail: teppei.j.yasunari@nasa.gov.

measurements of (1) surface albedos based on radiation measurements, snow depth, and impurities in the snow surface layer (dust; Elemental Carbon (EC); OC) by Aoki et al. (2011), (2) meteorological observations including snow depth by Japan Meteorological Agency (JMA), (3) atmospheric aerosol information (EC concentration and absorption coefficient by the co-authors; aerosol optical thickness (AOT) by Aoki et al. 2013), and (4) total dust deposition flux during precipitation (called TDP) by Osada et al. (2011). We considered EC as BC (see Section 2; SI). We summarize as follows: Section 2, the methodology and data; Section 3, off-line sensitivity LSM simulations with GOSWIM in Sapporo, compared to the observations; and Section 4, the current performance on SDE at Sapporo in a global GEOS-5 experiment, compared to the observations. See the detailed information on the observations above in the Supplemental Information (hereafter called SI).

2. GOSWIM, methods, and data

The details of GOSWIM are summarized in Fig. 1 and SI. Figure 1 is the schematic of the relationships between GOSWIM and the other GEOS-5 modules. Currently the mass concentration scheme is separately calculated outside of the snowpack model (currently 3 snow layers) (Lynch-Stieglitz 1994; Stieglitz et al. 2001) in the Catchment LSM (Ducharne et al. 2000; Koster et al. 2000). The GOSWIM calculates the mass concentrations of the LAA depositions directly, using outputs from Goddard Chemistry Aerosol Radiation and Transport (GOCART) module (Chin et al. 2000, 2002; Ginoux et al. 2001; Colarco et al. 2010), coupled into NASA GEOS-5 (e.g., Rienecker et al. 2008; Nowottnick et al. 2011).

In this paper, we carry out one-winter off-line simulations at Sapporo, Japan, during 2007/2008 with the GOSWIM-included Catchment LSM. In addition, we use the direct outputs at Sapporo from a global on-line GEOS-5 simulation with GOSWIM (two test global experiments in SI were not included in the main experiments). For the off-line simulations, the LSM model with GOSWIM are forced by 1-hourly, observation-based meteorological data, for which the data treatment is based on the method of Yasunari et al. (2011), and dust, BC, and OC depositions from the direct outputs of the global on-line GEOS-5 simulation at the location grid point in Sapporo (see SI). The meteorological input data are produced based on the Automated Weather Station at the Sapporo District Meteorological Observatory that is maintained by JMA (hereafter called AWS/JMA; see the JMA website in Japanese: http://www.data.jma.go.jp/obd/stats/etrn/index.php) with some estimated variables (see SI). The snow samples for dust, EC, and OC measurements were taken at the backyard of the Institute of Low Temperature Science (ILTS), Hokkaido University by Aoki et al. (2011), in which those samples were measured after the samplings. The EC was measured by their study but they considered EC as BC based on the field measurements by Miyazaki et al. (2007) and we followed this. Their mass concentrations in the top 10 cm are used to validate model results. See more details in SI.

The main settings of four off-line LSM simulations and a global on-line GEOS-5 simulation are summarized in Tables 1 and 2 (also see SI): Exp 1 is mostly identical to the Fortuna 2.5 version of GEOS-5 land surface model settings for global simulation except for some treatments (Table 2; see SI); Exp 0 is similar to Exp 1 but with zero aerosol depositions; Exp 2 is similar to Exp 1 except that dust and BC deposition rates are increased by factors of 4.3 and 3.06, respectively. These factors were determined based on: (1) comparison on TDP between an observation at Sapporo by Osada et al. (2011) and the outputs from the global GEOS-5 test experiments (only discussed in SI) (Table S3; see SI); (2) comparisons between atmospheric BC (EC) observations at Sapporo and simulated surface mass concentrations of BC by the main global experiment (Exp GEOS-5) (Fig. S4; see SI); Exp 2-2 is similar

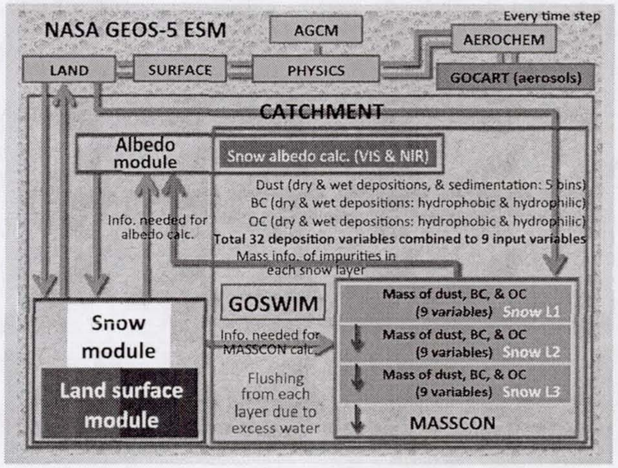

Fig. 1. Schematic of the relationship between GOSWIM in Catchment LSM and other GEOS-5 modules in NASA GEOS-5 ESM. The lines in orange, gray, and green correspond to the aerosol deposition variables from GOCART, calculated masses of impurities in the snow layers, and other GEOS-5 variables, respectively. Information for the inputs into the albedo module includes not only snow-related variables but also other land-related ones. The main inputs for the snow albedo calculations are snow water equivalent (SWE), mass of snow impurities (five bins of dust; hydrophobic and hydrophilic BC and OC), snow depth, and heat content in each snow layer. In addition, solar zenith angle, and direct and diffuse beams of incoming visible (VIS) solar radiations are used. The outputs of albedo variables are direct and diffuse components of snow-free and snow albedos in VIS and near infrared (NIR). The main inputs for the mass concentration scheme, MASSCON (see SI), are SWE before and after the snow module calculation, snow depth, fraction of ice, and flushing water flux in each snow layer. In addition, the aerosol depositions (dust, BC, and OC) from GOCART, snowfall rate, time step information, minimum snow density (i.e., new snow density; 150 kg m^{-3} in this study and the current GEOS-5 setting as default), and snow cover fraction (SCF) are used. In MASSCON, the new aerosols are deposited on the top snow layer, considering SCF. Then the mass concentrations in each snow layer are calculated, depending on the different conditions (six cases; Eqs. 2–7 in SI). First, the mass of impurities is re-layered in one of six conditions. Then, the mass flushing to the lower snow layer, due to excess water in the snow, is further considered with Eq. 8.2 in SI. Under the condition with SCF of less than 1, the partial masses of each constituent in each snow layer in each Catchment tile are permanently lost, depending on the ratio of water flow from the bottom of the snow layer (i.e., permanently lost SWE) to the total SWE at the current time step. The calculated masses of the impurities in each snow layer are saved but the mass concentrations are not. The current setting of the maximum snow depth for the top snow layer is 0.08 m. See more details in SI. The information of the main GEOS-5 structure outside of Catchment is also available at Code 600 website of NASA: (see at: http://sciences.gsfc.nasa.gov/600/highlights/stories/gpus.html).

Table 1. Summary of the experiments on the off-line Catchment and the global GEOS-5 simulations.

Exp. Name	Dust deposition to snow	BC deposition to snow	OC deposition to snow	Simulation type
Exp 0	No	No	No	Off-line at Sapporo
Exp 1	Yes	Yes	Yes	Off-line at Sapporo
Exp 2	Deposition rate × 4.3	Deposition rate × 3.06	Yes	Off-line at Sapporo
Exp 2-2	Deposition rate × 4.3	No	Yes	Off-line at Sapporo
Exp GEOS-5	Yes	Yes	Yes	Global

Note. The multiplied numbers denote the increased deposition rates.

Table 2. Data and main boundary conditions in the off-line Catchment LSM and global on-line GEOS-5 experiments (See more in SI).

Experiments	Data and main boundary conditions
Exps 0, 1, 2, and 2-2	Off-line GOSWIM experiment with Catchment LSM at Sapporo with an off-line simulation driver based on Yasunari et al. (2011)
	Simulated aerosol depositions (dust, BC, and OC); Extracted at Sapporo from Exp GEOS-5 global experiment (see the deposition treatments in Table 1)
	Assumed the ground cover vegetation (grassy-type vegetation) at Sapporo as same as Yasunari et al. (2011)
	JMA observation-based meteorological data (estimated variables included) for inputs; Data treatment method based on Yasunari et al. (2011)
	Cloudy (diffuse) condition treatment to all the snow albedos: Based on Yasunari et al. (2011)
	Weight fractions (80% and 20% for direct and diffuse components) calculating broadband VIS and NIR snow albedos based on Melloh et al. (2002) in the off-line driver
	Switching the simulated snow albedos to vegetation albedos after the snow disappearance for output purpose; Under SWE being less than the minimum value of 0.013 kg m^{-2} (Different from the minimum SWE for areal fraction)
Exp GEOS-5	NASA GEOS-5 on-line global experiment and extracted outputs at Sapporo (1-hourly mean outputs)
	Aerols simulated in GOCART module (Chin et al. 2000; 2002; Ginoux et al. 2001; Colarco et al. 2010)
	GOSWIM/Catchment LSM calculation over the model-defined land tiles; Excluding land ice (i.e., glaciers and the ice sheets) and sea ice parts
	Replayed with MERRA re-analysis data (Rienecker et al. 2011) for main atmospheric variables (every six hours); Replayed variables: pressure thickness, wind UV, specific humidity, virtual temperature, and ozone data
	Cloudy (diffuse) condition treatment to all the snow albedos: Under the ratio of direct beam to the sum of direct and diffuse beams in VIS of less than 0.1
	Biofuel and fossil fuel emissions until 2006 based on the emission dataset; Described by Diehl et al. (2012) (data in 2006 used after 2006)
	Biomass burning emissions based on the Quick Fire Emission Data set (QFED); Described by Petrenko et al. (2012) and Darmenov and da Silva (2013)
	Prescribed sea surface temperature based on in-situ and satellite data (Reynolds et al. 2002); Also used in MERRA re-analysis data (Rienecker et al. 2011)

to Exp 2 but BC depositions are set to zero depositions so as to discuss local BC SDE; Exp GEOS-5 uses direct outputs from the main global GEOS-5 experiment with GOSWIM, which is also used to extract the 1-hourly mean aerosol deposition rates for the forcing data in the off-line simulations above (see SI).

3. Off-line GOSWIM/Catchment LSM experiments in the winter of 2007/2008

Exp 1 is the control off-line simulation that provides the basic information regarding the overall estimate of SDE at Sapporo, forced by the observation-based meteorology and the direct aerosol depositions from the GEOS-5 global experiment. Seasonal migration of simulated snow albedos in visible (VIS) and near infrared (NIR), and snow depth were reasonably obtained (Fig. 2a). VIS snow albedo evolutions from the snow accumulation to the melting periods are closely related due to the evolutions of the snow impurities (Figs. 2 and 3). The seasonal migrations of simulated mass concentrations of dust, BC, and OC were also captured (Fig. 3a). After snowfalls, the simulated mass concentrations in the top of snow layer decreased because of the fresh snowfall. However, the model clearly underestimates the dust and BC mass concentrations except for the BC in the early winter. As a result, simulated VIS snow albedo was significantly higher during the melting period. Note that the observed impurity data from the last two snow samples taken in Sapporo, on March 28 and 31 in 2008, are probably not representative because those samples were taken without snowpit works, after the ending dates of the observed snow at ILTS and AWS/JMA (Table 3). We considered that those samples were taken from existing patchy snow. Under the zero aerosol depositions (Exp 0; Fig. S3), even higher VIS snow albedo was seen and the snow cover duration was extended, which was consistent with Yasunari et al. (2011). The importance of the SDE consideration in the melting period agrees with the previous studies (e.g., Painter et al. 2007; Yasunari et al. 2011; Niwano et al. 2012). In addition, there were differences of nearly two orders of magnitude in the VIS mass absorptions and in the mass concentrations in snow between dust and BC, respectively (Table S1; Fig. 3). This suggests that both the contributions on snow albedo reductions cannot be ignored, as also was suggested by Flanner et al. (2009).

In Exp 2 (a sensitivity off-line simulation), the dust and BC deposition rates were increased by the factors of 4.3 and 3.06, respectively (Table 1; see SI). From the discussion in SI, simulated TDP (the GEOS-5 test experiments in SI) and surface BC concentrations (Exp GEOS-5) at Sapporo by GEOS-5 had low biases, compared to observations (Table S3; Fig. S4). These were probably due to GEOS-5 missing local emission information on BC and dust (or/and underestimates of dust transport and deposition; see SI), even though column total aerosol information (AOT) in Sapporo (ILTS) was better simulated (Fig. S6) compared to the surface BC variations with the observed BC (EC) and absorption (Figs. S4 and S5). However, the simulated AOT still had lower bias of up to about 17% against the observation (based on the slope in Fig. S6). The simulated VIS albedo in Exp 2 during the snow accumulation period slightly worsened (Fig. 2b), suggesting that the increase of the deposition rates was necessary but still imperfectly explains the observed albedos as discussed later. However, overall, this sensitivity off-line simulation was the best simulation to explain the observations (Figs. 2 and 3; Table 3). We found that there were clear improvements on the timings of snow albedo drop-offs, the ending date of the snow, and the magnitudes on snow impurities (Figs. 2b and 3b; Table 3). The results in Exp 2 could well explain the discrepancies between the observations and Exp 1 in Sapporo (Figs. 2a, 2b, 3a, and 3b), mainly attributing them to simulated less dust and BC depositions in Exp 1.

Under the assumed best condition on aerosol depositions (Exp 2), we further explore the effect of zero BC deposition as Exp 2-2 (i.e., BC off SDE). This sensitivity experiment addresses the question: if we could somehow remove BC from the atmosphere in a major urban city, Sapporo, how long would snow cover duration change under the current meteorological conditions? Exp 2-2 clearly showed that removing BC SDE resulted in snow cover

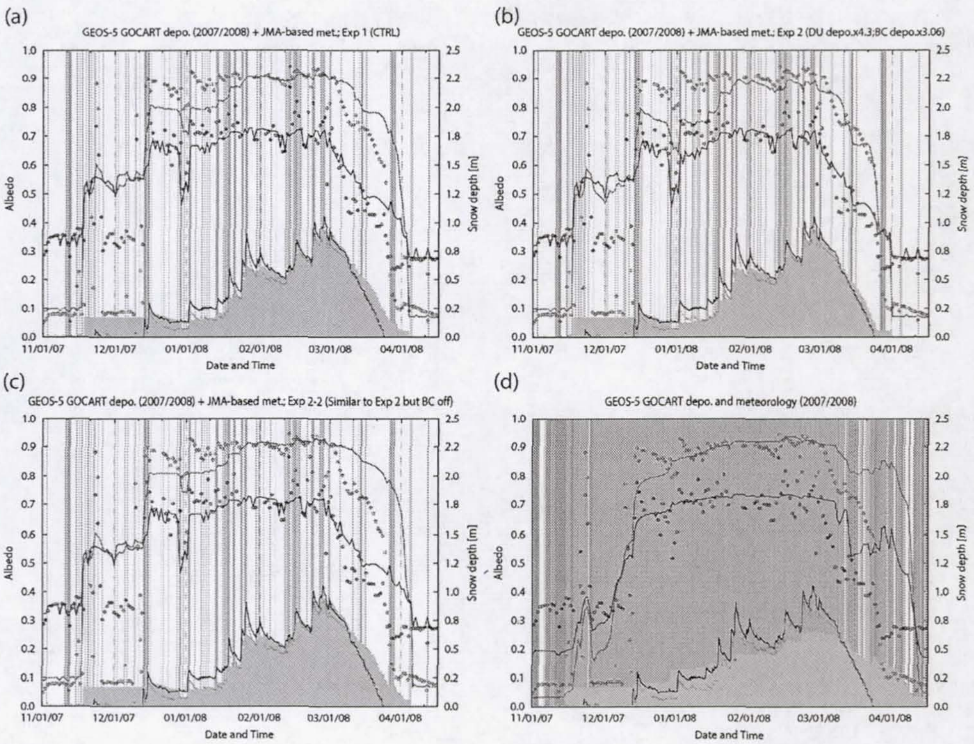

Fig. 2. Surface albedo (vegetation and snow), snow depths, and precipitation timings for the one winter off-line Catchment LSM simulations and outputs from one global GEOS-5 simulation for (a) Exp 1, (b) Exp 2, (c) Exp 2-2, and (d) Exp GEOS-5, with the observations by JMA and Aoki et al. (2011). Comparisons on VIS (red) and NIR (blue) surface albedos (1-hourly mean data at noon), and snow depth (scale on the right side; AWS/JMA in black; ILTS in green; simulation in pink) between the observations and simulations were carried out in the main text. For surface (vegetation and snow) albedos, points and solid lines are observations and simulations, respectively. Error data, and zero or negative numbers were excluded. Vertical solid lines in turquoise and gray indicate the timings of rainfall and snowfall determined with the AWS/JMA observations for (a)–(c) and outputs from Exp GEOS-5 for (d), in which observed air temperature of 0 degree Celsius and simulated snow and rain components were used to judge whether rainfall or snowfall.

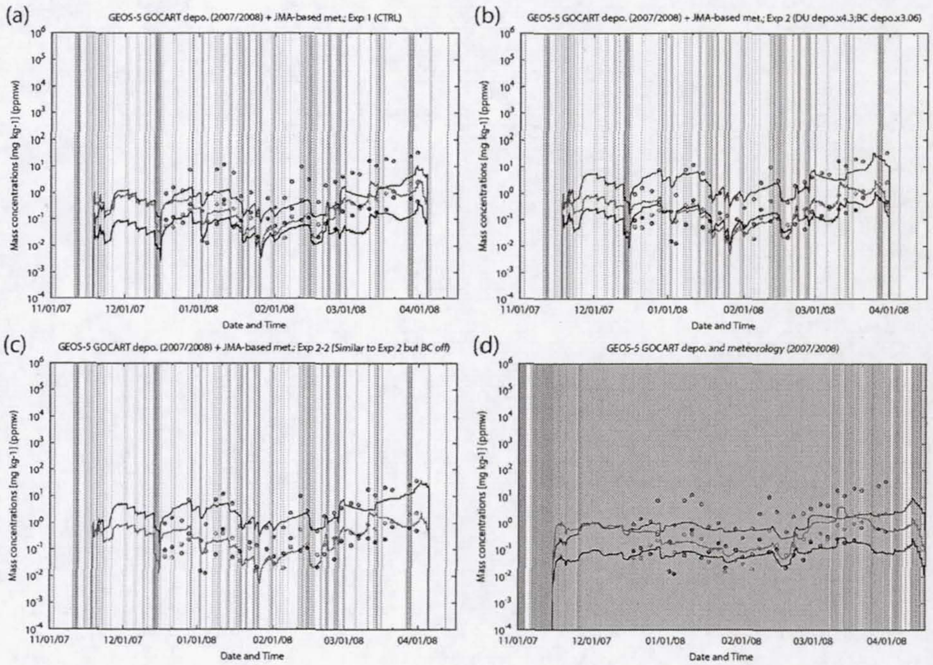

Fig. 3. Simulated mass concentrations of dust (blue), BC (black), and OC (red) in the top snow layer (maximum: 0.08 m) for (a) Exp 1, (b) Exp 2, (c) Exp 2-2, and (d) Exp GEOS-5, compared to the observed mass concentrations in the top 0–10 cm of the snow surface by Aoki et al. (2011) (points in the same colors as the ones simulated; also see SI). As mentioned in Section 2, we consider the observed EC as BC. The simulated mass concentrations, which are calculated from each mass of the impurities and SWE in the top snow layer, are shown in solid lines. All are also shown in log scale. Vertical solid lines in turquoise and gray are as same as the rainfall and snowfall timings, respectively, as explained in Fig. 2.

Table 3. RMSEs between observations and simulations, and snow ending dates.

	snow depth [m] (ILTS)	snow depth [m] (AWS/JMA)	albedo SW	albedo VIS	albedo NIR	Snow ending date
Exp 0	0.116	0.111	0.114	0.144	0.092	April 8, 2008
Exp 1	0.090	0.093	0.096	0.107	0.087	April 4, 2008
Exp 2	**0.068**	**0.091**	**0.087**	**0.095**	**0.083**	**April 1, 2008**
Exp 2-2	0.101	0.100	0.102	0.121	0.089	April 5, 2008
Exp GEOS-5	0.150	0.161	0.129	0.136	0.120	April 16, 2008
ILTS	n/a	n/a	n/a	n/a	n/a	March 24, 2008
AWS/JMA	n/a	n/a	n/a	n/a	n/a	March 25, 2008

Note that n/a is "not applicable". The bold numbers and character are the best RMSEs and closest snow ending date to the observed ending dates of snow depth.

duration lasting four days longer, compared to Exp 2 (Fig. 2b and 2c; Table 3). The VIS albedo in the melting period was higher than that of Exp 1 (Fig. 2a and 2c). Spring snow cover reductions with warming trends have been discussed (Brown 2000). Even under the warming trend, snow cover duration might possibly be extended locally to this degree, if we can somehow remove the BC in an urban city, though it depends on the pollution levels there.

Comparison between Exps 2 and 2-2 (Figs. 2b, 2c, 3b, and 3c) suggests that the difference on VIS snow albedo during the snow accumulation period could be mainly explained by the BC depositions and its light absorption degrees in snow because of the simple difference (with/without BC depositions) and the pre-melting period. However, uncertainties on snow albedo calculation in GOSWIM are also contributed by other factors such as depositions and optics of the other impurities, snow density treatment for fresh snow, estimate of snow specific surface area, etc. All these uncertainties influence the whole performance of SDE simulation. Detailed observations of these components are essential to reduce the uncertainties and then to improve SDE estimates in the future modeling.

4. Direct outputs at Sapporo from a global on-line GEOS-5 experiment

Although the off-line GOSWIM/Catchment LSM simulations could reasonably simulate seasonal snow and snow impurities along time evolution with the prescribed LAA depositions and meteorology (Section 3), global GEOS-5 simulation currently has an issue apart from SDE calculation. Exp GEOS-5 showed a further extension of snow duration at Sapporo (Fig. 2d; Table 3) in which we could see frequent snowfalls in the winter and even in the spring. However, the observation showed no snowfall in the melting period (Fig. 2a, 2b, and 2c). The gradual increase of the simulated snow depth in Fig. 2d implies continuous weak modelled snowfall. In addition, increased horizontal resolution could generate higher biases on precipitation at Sapporo (Table S4; see SI). The simulated TDP and surface BC mass concentration by GEOS-5 at Sapporo also underestimated the observations of TDP by Osada et al. (2011) (Table S3) and the atmospheric BC (EC) mass concentration (Fig. S4). Thus the underestimates of simulated LAA in snow and extended snow cover duration in Figs. 2d and 3d are reasonable. Therefore, the projection of exact timings of the snow ending date in global GEOS-5 simulations would largely be affected by the performances of both the local precipitation and the LAA depositions.

5. Conclusions

We have introduced the developed GOddard SnoW Impurity Module (GOSWIM) for NASA GEOS-5 ESM, validated with observations of albedos, snow depth, and snow impurities in the snow surface in Sapporo, Japan. Under the prescribed meteorological and LAA deposition data, GOSWIM successfully simulated seasonal migrations of snow albedo, snow depth, and mass concentrations in snow. However, the mass concentrations of dust and BC in snow are significantly lower compared to the observations except for the BC in the early winter, due mainly to the underestimates of modelled dust and BC depositions. A sensitivity simulation increasing BC and dust deposition rates aptly explains the underestimates. Under the best guess condition of LAA depositions in the sensitivity experiment, we found that removing BC deposition possibly extend the snow cover duration by four days in Sapporo. It suggests that if we can somehow clean up BC from the atmosphere in Sapporo, the extension of snow-covered time period would be possible. On global GEOS-5 experiments, simulated local precipitation and LAA deposition amounts on snow would largely affect its performance on local SDE.

Although GOSWIM has been developed with many available observations in Sapporo, more detailed observations are necessary in the future studies to reduce the uncertainties on modelled SDE and its climate feedbacks in global models. The flushing effect of LAA in snow is still uncertain due to limited observations (e.g., Conway et al. 1996; Painter et al. 2012; Doherty et al. 2013). Optical properties of LAA in snow also have large uncertainties because of the unknown mixture condition of the constituents with snow, as mentioned for BC in Flanner et al. (2012). Observations to improve snow water equivalent (SWE) (i.e., with observations on precipitation and SWE loss processes), mass of the LAA (i.e., with observations on deposition and post-depositional processes of LAA in timely high resolution such as daily or shorter interval), proper total absorption in the mixture condition of LAA (i.e., with observations on optical properties of individual and mixed LAA in snow), and snow physical properties in modelled snowpack are the keys to future studies, as also suggested by Forsström et al. (2013) and mentioned for the forcing uncertainty in the latest IPCC report by Boucher et al. (2013).

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Supplement

Supplemental Information includes text, Tables S1–S4, and Figs. S1–S6.

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